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Scientific Knowledge and Knowledge Needs in Climate Adaptation Policy

A Case Study of Diverse Mountain Regions

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Mountain ecosystems around the world are recognized to be among the most vulnerable to the impacts of climate change. The need to develop sound adaptation strategies in these areas is growing. Knowledge from the natural sciences has an important role to play in the development of adaptation strategies. However, the extent of and gaps in such knowledge have not been systematically investigated for mountain areas. This paper analyzes the status of knowledge from natural science disciplines and research needs relevant to the national and subnational climate adaptation policies of 1 US state (Washington) and 7 countries (Austria, Bhutan, Colombia, Germany, Nepal, Peru, and Switzerland), in particular the elements of those policies focused on mountain areas. In addition, we asked key individuals involved in drafting those policies to answer a short questionnaire. We found that research needs mainly concern impact and vulnerability assessments at regional and local levels, integrated assessments, and improved climate and socioeconomic data. These needs are often related to the challenges to data coverage and model performance in mountainous areas. In

these areas, the base data are often riddled with gaps and uncertainties, making it particularly difficult to formulate adaptation strategies. In countries where data coverage is less of an issue, there is a tendency to explore quantitative forms of impact and vulnerability assessments. We highlight how the knowledge embedded in natural science disciplines is not always useful to address complex vulnerabilities in coupled human and natural systems and briefly refer to alternative pathways to adaptation in the form of no-regret, flexible, and adaptive management solutions. Finally, in recognition of the trans- and interdisciplinary nature of climate change adaptation, we raise the question of which knowledge production paradigms are best able to deliver sustainable adaptations to growing environmental stressors in mountain regions.

Keywords: Climate change; climate change impact; vulnerability; adaptation policy; policy-relevant knowledge.

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Introduction

During this century, the resilience of many ecosystems is likely to be challenged by climate change and other anthropogenic drivers such as land-use change, pollution, and overexploitation of natural resources (Settele et al 2014). Mountain ecosystems are considered particularly sensitive and vulnerable to climate change (Körner et al 2005; Valdivia et al 2010; Field et al 2014), and an increasing number of people depend on their upstream and downstream services (Huddleston et al 2003). Mountain regions in developing countries are recognized to be among the most exposed to the impacts of climate change (McDowell et al 2013). There is growing concern about how to cope with and adapt to climate change in fragile mountain ecosystems, particularly in countries with substantial mountainous areas (Grêt-Regamey et al 2012). The recently published research priorities report of the Programme of Research on Climate Change Vulnerability, Impacts and Adaptation (PROVIA 2013)

also stresses the importance of understanding adaptation to climate change in specific human and natural systems such as mountain regions.

Understanding adaptation in coupled human and natural systems requires understanding of the degree and nature of observed and projected climate impacts, current and future vulnerability, and the adaptive capacity of a country or region (Field et al 2014). As documented in the Intergovernmental Panel on Climate Change's (IPCC's) fifth assessment report (Field et al 2014), the scientific community has increasingly addressed the topics of impacts, vulnerability, and adaptive capacity, and its commitment to investigating these topics has been influential at all policy levels. Adaptation strategies in fact are often based on, or triggered by, scientific knowledge on climate systems, impacts, vulnerabilities, and adaptation (Biesbroek et al 2010). Scientific information and knowledge can lead to an effective response to adverse impacts of climate change, thus reducing vulnerabilities and enhancing adaptive capacities

(Patwardhan et al 2009). This can be especially helpful in those areas most exposed to the impacts of climate change such as mountain regions.

McDowell et al (2014), in a review of adaptation actions in mountain regions, highlighted that synthesis work on climate change impacts and adaptation actions is paramount for increasing the effectiveness of adaptation policy. However, this review also revealed that there is limited documentation of the impacts of climate change on human systems and adaptation in mountain regions. Biesbroek et al (2010), in a comparative synthesis of national adaptation strategies in 10 European countries, found that only 2 countries, Germany and Spain, specifically prioritize or plan to prioritize mountain zones in their adaptation policy.

In their analysis of the types of knowledge needed to support adaptation policies in general, Hanger et al (2012) pointed out the importance of impact and vulnerability assessments, socioeconomic analyses of adaptation, and assessment of the costs of adaptation measures, as well as the need to reduce uncertainty. Similarly, Patwardhan et al (2009) emphasized that understanding current and future vulnerability and its interactions with climate stresses requires more studies on exposure, sensitivity, adaptive capacity—all 3 components of vulnerability as defined in the IPCC's fourth assessment report (Pachauri and Reisinger 2007)—and their interaction with environmental, social, and economic conditions.

Numerous studies have analyzed national adaptation policies in European and other developed countries and the mechanisms by which they were formulated (Gagnon-Lebrun and Agrawala 2006; Massey and Bergsma 2008; Swart et al 2009), but they only briefly discuss what scientific contributions shaped such documents (Swart et al 2009). A more global comparison focused on needs and gaps in adaptation research in mountain countries is currently lacking (McDowell et al 2014; Huggel et al 2015). Although important progress has been made in investigating the interface between science and policy in climate adaptation (Vogel et al 2007; Dilling and Lemos 2011; Hanger et al 2012; Lemos et al 2014), less attention has been devoted to analyzing scientific contributions to adaptation policy with the aim to address research needs and gaps (Hanger et al 2012; Huggel et al 2015).

In this study we analyzed the scientific knowledge that supported the development of nation- or statewide adaptation policies in 8 locations (7 countries and 1 US state) that represent different mountain regions and socioeconomic conditions. We performed a comparative analysis of Austria, Bhutan, Colombia, Germany, Nepal, Peru, Switzerland, and Washington State, USA, which we chose through purposive sampling in July 2012. We opted for a case-study design in order to obtain a contextualized and comparative analysis of the selected locations

(McDowell et al 2014). We also looked for any mention in each policy of scientific knowledge specific to mountain areas and possible issues associated with the complex topography of these areas, conducted a questionnaire survey, and reflected on knowledge gaps from our own expert natural science perspective. We are aware that the development of adaptation strategies and measures is a multidimensional process, ideally involving multiple actors from science, governmental and nongovernmental institutions, and civil society, and that in addition to exploring the natural science knowledge base, it is important to explore gaps in the social sciences and analyze how climate change adaptation policies are negotiated and agreed upon at different levels of social organization. But that goes beyond the scope of the present paper and would require a different research approach.

Framework for data analysis

Data were collected from national or state climate change adaptation policies available in a language known by the authors (English, German, or Spanish) and through questionnaires submitted to policy-makers responsible for these policies. Data were gathered from policy documents in an inductive way: the documents were read and then information was systematically selected (Altheide et al 2008; Bryman 2012). The information was selected based on the objectives of the present paper, namely to find out what scientific knowledge contributed to the strategies and what research needs could be identified. The research needs were identified based on explicit statements in the policy documents we reviewed, additional findings from an in-depth qualitative document analysis of those documents (Altheide et al 2008), and the informants' responses to the questionnaire.

Finally, we looked for recurrent topics influencing the scientific knowledge relevant to the strategies. In this context, we recognized that the approach to adaptation policy development influences the way scientific knowledge contributes to the policy (Addor 2015). In particular, the choice between a top-down or bottom-up approach dictates how scientific knowledge supports the development of the strategy. A *top-down* approach starts from a scientific perspective (assessment of global climate change and its impacts) and proceeds to assess vulnerabilities at a regional or sectoral level. A *bottom-up* approach starts from the local socioeconomic context and vulnerabilities (Swart et al 2009; Addor et al 2015). A third possibility is to use a top-down approach but attempt to integrate different degrees of participation at the local level; we labeled this approach *inclusive*.

To analyze the contribution of scientific knowledge to climate-change adaptation strategy, as well as remaining

research needs, we classified research contributions in 3 broad areas (adapted from Swart et al 2009):

1. Climate system dynamics;
2. Impacts of climate change on environmental and human systems;
3. Vulnerability to climate change and the factors that makes a system vulnerable.

In this context, we defined vulnerability, following the IPCC's fourth assessment report (Pachauri and Reisinger 2007: 883), as "the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes." We are aware that more recent IPCC reports have shifted away from this conceptualization to a more risk-based approach (Field et al 2014). In this new conceptualization, vulnerability and exposure are 2 separate components of risk to climate extremes and climate-related events. However, at the time the adaptation policies were developed, the prevalent vulnerability paradigm followed the IPCC'S fourth assessment report.

The documents were screened to identify topics pertaining to mountain areas. The focus was mainly on natural science topics, partly because of our academic background and partly because social science topics rarely occurred in the documents in relation to mountains.

Review of adaptation policy documents

We analyzed official National Adaptation Strategies and National Adaptation Plans for Action. National Adaptation Strategies are understood in this paper as a mix of policy and measures to address the impacts of climate change, variability, and extremes, and to reduce the vulnerability of a country (Biesbroek et al 2010). National Adaptation Plans for Action refers to a program of the United Nations Framework Convention on Climate Change (UNFCCC) that aims at identifying the priority needs for adaptation of least-developed countries. We also drew on National Communication Reports to the UNFCCC, especially when the other 2 documents were not available. In the framework of the UNFCCC, these are national reports that specify how countries are implementing the convention in terms of adaptation and mitigation to climate change. A full list of the documents that were consulted is provided in *Supplemental material*, Table S1; (<http://dx.doi.org/10.1659/MRD-JOURNAL-D-15-00016.S1>). The documents were analyzed using qualitative document analysis (Altheide et al 2008). Information was extracted in 2 main categories: (1) approach to adaptation policy development (top-down, bottom-up, or inclusive) and (2) contribution of scientific knowledge to the strategy and remaining research needs.

In a further step, scientific reports on climate scenarios and models as well as impact and vulnerability assessments were reviewed if cited in the official policy

documents (*Supplemental material*, Appendix S1: <http://dx.doi.org/10.1659/MRD-JOURNAL-D-15-00016.S1>).

Questionnaire

A questionnaire (*Supplemental material*, Appendix S2: <http://dx.doi.org/10.1659/MRD-JOURNAL-D-15-00016.S1>) was sent by email to the person or unit responsible for the adaptation policy of each targeted country or state. Feedback was received from all but Bhutan; for that country, our analysis was limited to information available in the National Adaptation Plan for Action. Informants included researchers in "boundary organizations" (Cash et al 2003), advisors, policy-makers, and decision-makers. The questionnaire focused on the same key themes as the literature search (approach to adaptation policy development and contribution of scientific knowledge), and answers were categorized accordingly and analyzed using qualitative document analysis.

Results

Approach to adaptation policy development

Most adaptation strategies analyzed in this study used a top-down, inclusive approach. The focus of the study was on actions taken at the national level, which often include recommendations for linkages with regional, local, and sectoral levels. In Germany and Austria, interactions with subnational regions seem to be more explicit in the adaptation strategy encouraging a certain level of initiative at the local level. Government organizations are the drivers behind the strategies, with support from government and research institutions such as the Meteorology, Hydrology, and Environmental Studies Institute in Colombia. Nepal and Bhutan take a bottom-up approach that benefited from extensive consultations at the grassroots level. Generally, National Adaptation Strategies follow a top-down approach, whereas National Adaptation Plans for Action consider existing coping strategies at the grassroots level and build on them to identify priority activities in the short term, rather than using scenario-based modeling to assess future vulnerability and creating long-term national adaptation plans.

Contributions from science and perceived research needs

This section focuses in turn on the 3 categories of scientific knowledge mentioned earlier: climate system research, impact assessments, and vulnerability assessments. Results are summarized in Table 1 with additional information provided in *Supplemental material*, Appendix S1; (<http://dx.doi.org/10.1659/MRD-JOURNAL-D-15-00016.S1>) and further tables.

Climate system research: This area refers mainly to climate models and their results (Table 1). General circulation

TABLE 1 Summary of the contribution of scientific knowledge on climate system research to countries' adaptation policies, research needs identified, and mountain-specific issues associated with this body of knowledge.^{a)} (Table continued on next page.)

Location	Climate system research ^{b)}	Research needs ^{c)}	Mountain-specific issues
Austria	Based on SRES (Nakicenovic and Swart 2000), scenarios A1B and B1 from IPCC AR4 (Pachauri and Reisinger 2007) GCMs: ECHAM5, HadCM3 RCMs: MM5, CCLM (10 × 10 km) spacing (covering the entire Alpine region); period 2001–2050 Comparison of past and current climate: observations obtained from HISTALP	None identified	More robust climate change signal due to improved representation of the Alpine region in the RCMs. Changes in precipitation not as robust as temperature Changes in the Alpine regions are only shown for the second half of the 21st century
Bhutan	Based on SRES (Nakicenovic and Swart 2000), scenarios A1B and B2 from IPCC AR4 (Pachauri and Reisinger 2007) GCMs: HaDCM3, ECHAM5 RCM: PRECIS (22 × 22 km); 2010–2039 and 2040–2069 Comparison of past and current climate: observational data—monthly average precipitation and mean temperature for 1990–2003	Scarce data coverage, unclear data quality and reliability Need for reliable climate projections at relevant scales	Corrections for elevation might be responsible for different outputs of the 2 GCMs
Colombia	Based on SRES (Nakicenovic and Swart 2000), scenarios A2 and B2 from IPCC AR4 (Pachauri and Reisinger 2007) GCMs: ECHAM4 RCMs: MRI (Japan, 20 × 20 km), PRECIS (25 × 25 km), WRF (4 × 4 km for the Andes); Period covered 2011–2100 Comparison of past and current climate: observational data; data from climate stations and from satellites	Incomplete time series and accuracy issues for climate data	None identified
Germany	Based on SRES (Nakicenovic and Swart 2000), scenarios A1B, A2, and B1 from IPCC AR4 (Pachauri and Reisinger 2007) GCM: ECHAM5 RCMs: REMO, CLM, WETTREG, STAR (10 × 10 km resolution; 2021–2050 and 2071–2100) Comparison of past and current climate: data on temperature and precipitation 1901–2006 from the German Weather Service	None identified	None identified
Nepal	Based on SRES (Nakicenovic and Swart 2000), scenarios A2 and B2 from IPCC AR4 (Pachauri and Reisinger 2007) GCMs: HadCM3, HadAM3, ECHAM5 RCMs: REGCM3 (55 × 55 km, 2040–2070), PRECIS (25 × 25 km, 2070–2100) Comparison of past and current climate: data on temperature and precipitation 1971–2005, local people's perceptions	Limitations of GCM, RCM, and dataset for this region of the world; need for comparison of the 2 model types to produce more suitable models for Nepal Lack of data availability and accessibility	None identified

TABLE 1 Continued. (First part of Table 1 on previous page.)

Location	Climate system research ^{b)}	Research needs ^{c)}	Mountain-specific issues
Peru	Based on SRES (Nakicenovic and Swart 2000), scenarios A2, B2, and A1B from IPCC AR4 (Pachauri and Reisinger 2007) GCMs: CCSM3, CSIRO, ECHAM4, HadCM3, MRI, CGCM2 RCM (at basin level): RAMS (60 × 60 km and 20 × 20 km); statistical downscaling Comparison of past and current climate: observational data from the SENAMHI (1965–2006)	Improvements in data coverage and infrastructure	High mountains are treated as a separate region for the statistical downscaling Meteorological and hydrological data are lacking for mountain regions
Switzerland	Based on SRES (Nakicenovic and Swart 2000), scenarios A1B, A2 from IPCC AR4 (Pachauri and Reisinger 2007), and RCP3PD (CH2011 2011) RCM: based on ENSEMBLES 30 years mean (midyear 2035, 2060, 2085); seasonal and daily values with Switzerland divided into 5 regions Comparison of past and current climate: climate observations from 1864 onward; Meteo Swiss data; daily gridded (2 × 2 km resolution) and local daily (changes in temperature and precipitation for individual sites of the Swiss monitoring network at daily resolution)	None identified	Projecting climate scenario in Alpine region is recognized as a difficult task because of the topography Regional average is recognized as not meaningful for central Alpine region because of the complex nature of the climate; downscaled daily climate scenarios at station locations are better Temperature overestimation may occur in the Alpine region as a result of the methodological approach
Washington State	Based on SRES (Nakicenovic and Swart 2000), scenarios B1 and A1B from IPCC AR4 (Pachauri and Reisinger 2007) GCMs: CCSM3, ECHAM5 RCMs (Climate Impacts Group 2009): CCSM3 (36 km, 2030–2059), ECHAM5 (20 km, 2030–2059) Comparison of past and current climate: CRU data (Mitchell et al 2004).	None identified	RCMs are used to better understand the influence of subregional geographic variability (such as mountains) on future climate conditions

^{a)} HISTALP, Historical Instrumental Climatological Surface Time Series of The Greater Alpine Region; SENAMHI, Peruvian National Service for Meteorology and Hydrology; CRU, Climatic Research Unit of East Anglia.

^{b)} More details on the GCMs and RCMs are provided in *Supplemental material*, Appendix S1; (<http://dx.doi.org/10.1659/MRD-JOURNAL-D-15-00016.S1>).

^{c)} Research needs include gaps identified in the policy documents themselves, in replies to the questionnaire administered during this study, and based on the authors' assessment. Mountain-specific issues were identified during qualitative document analysis.

models (GCMs) are numerical climate models that provide a comprehensive representation of the global climate system at relatively coarse spatial resolution. In order to obtain results at the regional or local scale, 2 downscaling methods are available: (1) dynamical downscaling (or regional climate models [RCMs]), where a climate model of higher resolution (RCM) is run over a limited area, driven by output from a GCM, and (2) statistical downscaling, where local climate features based on observations are empirically related to large-scale climate features taken from a GCM. Few of the countries analyzed for this study calculated their own RCM. Most countries used combined results from multiple GCMs informed by the *Special Report on Emissions Scenarios* (SRES) (Nakicenovic and Swart 2000)

and Solomon et al (2007) (which contains a useful description of the scenarios discussed in this paper).

The SRES emission scenarios most often used were A1B, followed by A2, B1, and finally B2. In most cases at least 2 SRES scenarios were used, usually 1 each from the A and B scenario families. The reasons for considering multiple scenarios included the ability to (1) explore the impacts of a wide range of greenhouse-gas emission concentrations and (2) assess the impacts of business-as-usual fossil fuel emission scenarios as well as more optimistic scenarios of reduced emissions and the consequent reduced temperature increases. Moreover, the choice of the A2 scenario seems to have been due to its closer agreement with current emission trends.

Because none of the SRES scenarios had a probability assigned, the use of multiple GCMs and SRES scenarios (as done by all countries in the study) made it possible to assess ranges of uncertainties inherent in the emission scenarios and the climate models. Switzerland additionally used the emission scenario RCP3PD (CH2011 2011), which was developed for the Coupled Model Intercomparison Project Phase 5 of the latest IPCC assessment (Stocker et al 2013), illustrating an emission concentration pathway that stabilizes carbon dioxide-equivalent concentration near 450 parts per million by the end of the century, and as such corresponds to a limitation of global warming to less than 2°C over the preindustrial level (van Vuuren et al 2007).

All countries had a clear need for high-resolution spatial climate model output, as reflected in their considerable use of both statistical and dynamic downscaling approaches (RCMs). The need for high-resolution models was of particular importance in mountain settings. Small-scale and complex topography significantly influence meteorological processes and lead to a high spatial variability in climate variables as well as regional differences in the rate of change of these variables. In addition to high-resolution climate model data, it is also important to have reliable long-term climate observations in order to validate the climate models and to predict future trends (Kotlarski et al 2014). In countries with extensive and remote mountain areas, such as Bhutan, Colombia, Nepal, and Peru, we infer a clear need for reliable long-term climate observations and a robust scientific baseline. This is typically a challenging task, as the maintenance of a sufficiently dense observational network for reliable long-term monitoring is costly and challenging (in terms of technical issues and accessibility) (Salzmann et al 2012, 2015). This is also reflected in the research needs identified by the informants or mentioned in the policy documents, namely limitations in coverage, availability, and accessibility of current and past climate data (Bhutan, Colombia, Nepal, and Peru) and limitations in regional climate scenarios for specific regions of the world (Nepal and Bhutan).

Austria, Switzerland, and Washington State benefited from numerous reliable and long-term climate records and many RCM-based assessments, allowing a more robust analysis of the climate change signal versus the natural climate variability. A higher-resolution image of the mountain topography is useful for a better projection of climate impacts at scales relevant to planners and managers (local to regional), although uncertainty is not per se reduced with higher resolution (Hallegatte 2009). In Peru, the lack of meteorological and hydrological data was recognized as particularly important for mountain regions. In Bhutan, corrections for elevation led to mismatching outputs of the 2 GCMs used, as reported in the policy document.

Impact assessments: This area refers to assessments of the observed and projected impacts of climate change on natural and human systems (Table 2). The majority of the countries employed qualitative assessments or index/indicator-based assessments. Qualitative assessments often refer to expert judgments based on results of climate system dynamics assessments, combined with knowledge of previous impacts in the country, usually related to climate variability and extremes (OcCC 2007). Index-based assessments blend climate system information in the form of indices (calculated values used to describe the state of and changes in the climate system) with proxies for public health, ecosystem integrity, and other key factors (eg Fischer and Schär 2010; Buytaert et al 2011). Impact assessments are usually (eg in Austria, Bhutan, Switzerland, and Washington State) carried out at the sectoral level, which means exploring impacts of climate change on the different sectors of the economy. Washington State is the only one of the entities studied to have developed its own impact models for several economic sectors.

In Nepal, Bhutan, and Peru, local perceptions also constituted part of the formal impact assessment. Typically, interview-based studies evaluate how local people perceive changes in their environment, as related to climate change (Byg and Salick 2009; McDowell and Hess 2012).

In Austria, Germany, Peru, and Washington State, impacts were assessed specifically for mountain regions or mountain ecosystems. In Bhutan's National Adaptation Plan for Action, a chapter is dedicated to assessments of impacts on glaciers and the consequences of these impacts on people's wellbeing and security. In Switzerland, impacts and their consequences in the Alpine regions are highlighted throughout the adaptation strategy. However, in Colombia and Nepal, there was no assessment of impacts in mountain regions or in sectors relevant to their welfare and security.

This study's analysis of research needs found a clear concern in at least 3 countries about the lack of impact assessments at the local to regional scale. In Bhutan and Nepal, the research needs were mainly related to climate system dynamics. In Peru and Switzerland, the absence of socioeconomic impact assessments was a reason for concern. In Germany and Switzerland, information on interconnections between impacts and cross-sectoral assessment of impacts was identified as a significant knowledge gap. In Washington State, current data resources and scenarios were recognized as inadequate to assess impacts at scales relevant to planners and decision-makers.

Vulnerability assessments: This area refers to assessments of how the impacts of climate change will affect human and natural systems (Table 3). Half of the countries analyzed in this research based their vulnerability assessment on

TABLE 2 Summary of the contribution of impact assessments to countries' adaptation policies, research needs identified, and mountain-specific issues associated with this body of knowledge.^{a)}

Location	Impact assessments	Research needs	Mountain-specific issues
Austria	Sectoral qualitative impact assessment based on vulnerability assessments	None identified	Dedicated research on impacts of climate change in the Alpine area and specifically in the sectors of water and forest management in the mountains
Bhutan	Sectoral quantitative impact assessments	Knowledge gaps in impact assessments are a result of limited knowledge on climate system and sparse data coverage	Impact assessments are developed specifically for glaciers, which are treated as a sector
	Impact assessment based on expert judgments, stakeholder consultations, and local perceptions		
Colombia	Impact assessments that combine climate models with 2 indexes	Local to regional impact assessments	None identified
		Knowledge on the response of sensitive ecosystems to climate impacts	
Germany	Qualitative sectorial impact assessment	Impacts and interconnections between different impacts	Impacts specific to the Alpine region are discussed in a separate section
Nepal	Qualitative evaluation of impacts from RCM results, data trends, and local perceptions of changes	Knowledge gaps in impact assessments are a result of limited knowledge on climate system	None identified
Peru	Hydrological impact model at basin level; local knowledge and perceptions integrated	Local to regional impact assessments	Impacts in mountain regions are a focus of the policy
		Socioeconomic impacts	
Switzerland	Sectorial impact assessments based on OcCC 2007, which provides a qualitative assessment of impacts for Switzerland	Quantitative impact assessments	Impacts in Alpine regions are highlighted throughout the policy
		Regional to local impact assessments	
		Socioeconomic impacts	
		Cross-sectorial assessments	
		(Needs vary by sector)	
Washington State	Impact models for different sectors (Climate Impacts Group 2009)	Data and scenarios at scales useful for managers	Impacts on mountain ecosystems are treated in a separate, very short paragraph
			Climate in complex terrains and at different altitudes is poorly understood

^{a)} Research needs include gaps identified in the policy documents themselves, in replies to the questionnaire administered during the study, and based on the authors' assessment. Mountain-specific issues were identified during qualitative document analysis.

concepts outlined in the IPCC's fourth assessment report (Pachauri and Reisinger 2007), which defines vulnerability as a function of exposure, sensitivity, and adaptive capacity (Füssel and Klein 2006; Pachauri and Reisinger 2007). Colombia, Germany, and Nepal took a more quantitative approach to vulnerability assessment, combining indices and proxies for exposure, sensitivity, and adaptive capacity to derive a measure for vulnerability. In Nepal, vulnerability maps were produced

by using geographic information system (GIS)-based products.

Switzerland's vulnerability assessment, unlike the others, was not based on the IPCC's fourth assessment report's definition but on risks at the district level. This requires combining the climate hazard areas with the impact areas, where impact areas are assessed for different climate scenarios and socioeconomic situations (Holthausen et al 2013).

TABLE 3 Summary of the contribution of vulnerability assessments to countries' adaptation policies, research needs identified, and mountain-specific issues associated with this body of knowledge.^{a)}

Location	Vulnerability assessments	Research needs	Mountain-specific issues
Austria	Qualitative vulnerability based on IPCC AR4 (Pachauri and Reisinger 2007)	Better knowledge of adaptive capacity	None identified
Bhutan	Sector-specific vulnerability based on results of the impact assessments and on expert judgments, stakeholder consultations, and local perceptions	Knowledge gaps in vulnerability assessments are a result of limited knowledge on climate system and sparse data coverage	Vulnerability to glacier retreats and glacier lake outburst floods is assessed in a dedicated chapter that highlights the importance of the glaciated areas
Colombia	Vulnerability is given as a combination of indexes for impacts and adaptive capacity on a specific area of interest	Local to regional vulnerability assessments	Issues are related to a need to strengthen research activities and transfer of knowledge in high mountains and mountain wetlands
		Default parameters for climate and vulnerability assessments	
		Better socioeconomic and environmental data at the local scale	
Germany	Ongoing cross-sectoral, local to regional assessment based on quantification of impacts, sensitivity, and adaptive capacity	None identified	None identified
Nepal	Quantitative assessments at the local level based on IPCC AR4 (Pachauri and Reisinger 2007) definition; combination of risk/exposure maps, sensitivity maps, and adaptive-capacity maps at the district level; product is a GIS-based map with district vulnerability rankings	Knowledge gaps in vulnerability assessments are a result of limited knowledge on climate system and sparse data coverage	None identified
	Integrates local perceptions		
Peru	Qualitative assessment based on IPCC AR4 (Pachauri and Reisinger 2007) definition; uses physical vulnerability maps at the basin level	Better assessments at the regional to local level	Vulnerability of mountain regions are a focus area of the policy.
		Better data on mountain (especially high mountain) regions	Data on low, middle, and high microregions will be needed because different altitudes have different climates and seasonality
Switzerland	Vulnerability assessments not integrated in the strategy, which is based on a risk approach rather than on vulnerability	Cross-sectoral assessments	Risks in Alpine regions are well highlighted throughout the document
Washington State	Qualitative assessment based on IPCC AR4 (Pachauri and Reisinger 2007) and agency perceptions	None identified	None identified

^{a)} Research needs include gaps identified in the policy documents themselves, in replies to the questionnaire administered during the study, and based on the authors' assessment. Mountain-specific issues were identified during qualitative document analysis.

Peru uses a semiquantitative approach, blending a qualitative vulnerability assessment with physical vulnerability maps. Bhutan and Nepal include local perceptions in their vulnerability assessments, in

particular to evaluate adaptation capacities and sensitivities.

With regard to gaps in vulnerability assessment, some informants identified a lack of regional, local, and

socioeconomic assessments. In the case of Bhutan and Nepal, the informants and the policy documents underlined gaps with regard to community perception, autonomous adaptation, and vulnerability assessment through participative methods, in addition to the already mentioned gap in climate systems knowledge.

The mountain aspect in the vulnerability assessments mainly relates to assessing vulnerability to human and natural systems in sectors specific to mountain areas, such as water management, forest management, and mountain-related hazards (slope instabilities, rock and snow avalanches, glacier lake outbursts). Bhutan devoted a chapter to impact and vulnerability assessments related to glacier changes. Germany and Washington State each had a short mountain-related section (focused on the region in Germany's case and on the ecosystems in Washington State's case).

Discussion

Some of the study countries had a full adaptation strategy in place and were moving toward implementation and monitoring, whereas others were still in, or had just started, the process of collecting information that could be used to develop a strategy. Looking at knowledge about climate system dynamics and associated climate impacts, Germany and Washington planned to use more integrated and quantitative forms of assessment, whereas Bhutan, Colombia, Nepal, and Peru were mainly concerned with broadening their data coverage.

The scarcity of spatial and temporal data is a common drawback in climate and climate adaptation research, exacerbated in mountain areas where the climate is more variable and physical access and infrastructure often less developed, representing a challenge for long-term environmental monitoring (see for example Salzmann et al 2012). Quality assurance procedures at various points of the data chain are also greatly needed in mountain areas, together with standardized methods to account for missing data (Negi et al 2012). Efforts made to treat available observational data so that they become reliable and long-term time series are ongoing (eg Schwarb et al 2011), and the use of alternative data sets such as reanalysis data, interpolated data sets, or satellite-based products are an option when applied with care and prior evaluation, in particular for climate variables such as precipitation (eg Scheel et al 2011; Salzmann et al 2015).

In addition to scarcity of data, a clear lack of scientific capacity, funding, and institutional capacity is recognized for developing countries. Local universities and research centers often lack academic and technological skills that are essential for translating data outputs (from observations and models) into viable knowledge that supports policy-making (Huggel et al 2009, 2015; Salzmann et al 2009, 2014).

To bridge these gaps in natural science knowledge, some developing countries have pursued an approach that draws on the perceptions and perspectives of local people to estimate vulnerability dimensions. The assumption is that a better understanding of the adaptive capacity of individuals and communities (as a dimension of vulnerability) helps to reduce the knowledge gaps at the local and regional level (Nakashima et al 2012). Combining local knowledge (also termed traditional or indigenous knowledge) with other science findings for the purpose of climate adaptation planning is increasingly popular and a thriving field of scientific activity (Reyes-García et al 2015). Countries with abundant natural science knowledge to contribute to their adaptation strategies may also benefit from integrating local knowledge in adaptation planning in full consideration of the different social and institutional contexts (Leonard et al 2013).

In that context, it is important to recognize that local knowledge is based on its own values and epistemology, which may be independent of findings from natural sciences (Berkas et al 2000; Berkas 2009; Ford et al 2012). In terms of climate impacts, there is a higher level of confidence if both local knowledge and scientific studies detect the same phenomena, as for instance reported for changing water resources in the Andes of Peru (Bury et al 2011). In turn, inconsistencies or discrepancies between the 2 knowledge sources may indicate higher uncertainties and be related to different spatial or temporal scales. For instance, local knowledge refers to the effects of climate variability rather than climate change, as long-term changes are often difficult to perceive at the local level. An exception relevant for mountain countries may be glaciers and snow, whose changes have been reflected in local knowledge in the Andes, Himalaya, and other mountain regions (Byg and Salick 2009; Carey 2010; Brugger et al 2013).

Top-down inclusive approaches were preferred in the majority of the countries analyzed in this study. Swart et al (2009) suggested that a reason for this preference could be that the strategies tend to respond to concerns about global climate change and thus the adaptation policies are developed at the highest possible scale of competence, which is usually the national level. A problem with this approach is that the propagation of uncertainty along a model chain can quickly become important (Ludwig et al 2013). Several informants reported the challenges of obtaining robust climate signals from the climate projections in their mountain areas, and this was also pointed out in some of the policy documents. This could constitute a limitation in the assessment and subsequent choice of adaptation options. Moreover, RCMs and other downscaling methods do contain uncertainties and errors, which may still be too high for effective adaptation planning at a level relevant for managers and planners (Wilby and Dessai 2010).

Bhave et al (2014) suggested blending top-down and bottom-up approaches in order to deliver locally relevant adaptation policies, whereas Ludwig et al (2013) suggested a new approach in which adaptation strategies are developed based on current and future risks and then evaluated under future scenarios in order to test their robustness.

All 3 categories of scientific knowledge analyzed here have informed the development of adaptation strategies and policies. However, in the third area, vulnerability assessment, some studies have highlighted that relying too much on climate system dynamics and climate impacts might not be fully representative of future changes (Hallegatte 2009; Wilby and Dessai 2010). Knowledge of vulnerabilities, and associated exposures and coping capacities of coupled human and natural systems, is relevant to understand future changes (Field et al 2014). However, uncertainties in this body of knowledge can be larger than those in RCMs and need to be taken increasingly into account when formulating adaptation policies.

In response to this, a burgeoning body of literature has suggested that alternative paths to adaptation exist in the form of no-regret strategies (which yield benefits even without climate change), flexible strategies (which keep the cost of making wrong predictions as low as possible), “soft” strategies (institutional and financial solutions such as insurance, early warning systems, and capacity building) (Hallegatte 2009), and adaptive management (solutions based on the ability to change management practices in response to new scientific knowledge and insights) (Pahl-Wostl 2007). These approaches can be especially relevant in mountain regions, where the interactions of a complex topography with several interrelated social and environmental vulnerabilities exacerbate uncertainties (Beniston 2005).

Conclusions

Our analysis of national adaptation policies has shown that, at an initial stage, efforts were made to understand climate dynamics and develop emission scenarios. Observational records offered important sources of information against which to compare the output of climate models. Progress in the use of RCMs and other downscaling techniques allowed a number of countries to identify a more robust climate signal in their mountain areas, where topography often limits the performance of climate models. In these (mostly industrialized) countries, this stage has almost reached a saturation point and research efforts are now being devoted to impact and vulnerability assessments. These countries are quickly moving toward improvement in quantitative vulnerability and risk assessments, improved impact predictions at smaller scales, and the integration of socioeconomic issues. These improvements are highly relevant for

mountain areas where the interaction of multiple climatic stresses and diverse socioeconomic circumstances often makes adaptation more challenging than it is in lowland areas (McDowell et al 2014). Observational records are also being improved in Colombia, Nepal, and Peru, and there is hope that this will trigger more research funding and activities.

The following main conclusions can be drawn from this comparative case study analysis:

- In mountain regions, the available data are generally sparse and riddled with uncertainties, and spatial and temporal variability is generally high. Together, these factors make studies to inform adaptation policy particularly challenging. The application and use of climate models is standard, but the level of sophistication differs substantially between European and North American countries on the one hand and countries in Asia and South America on the other. Transfer of knowledge and skills among these countries can lead to a more equitable distribution of both.
- Top-down approaches dominate adaptation policy-making at national and subnational scales, but research and experience suggest that a flexible or blended approach could be more effective. Alternative approaches to adaptation such as no-regret strategies, flexible strategies, and adaptive governance can be more effective than studies relying heavily on past and current trends. This could be helpful in mountain regions where the complex topography and the interactions of multiple stressors and vulnerabilities can exacerbate uncertainties. In addition, a new approach to adaptation based on participatory risk assessment could overcome the limitations of both top-down and bottom-up approaches by combining both, and would be particularly useful in mountain areas.
- The methods adopted for impact and vulnerability assessments are broad, and identified research needs are mainly in assessments at the local level and assessments of socioeconomic vulnerability. More efforts are also needed to develop impact and vulnerability assessments at scales relevant for planners and managers in mountain areas.
- Finally, the analysis of scientific knowledge as reported in this study is only one of the many knowledge components that can contribute to the formulation and implementation of adaptation policy. Scientific knowledge, as elicited in adaptation policy at a very coarse level, can by no means fully capture the complex dynamics that contribute to a country's adaptation policy. Climate change adaptation is problem focused and trans- and interdisciplinary by nature, and increasingly entails the integration of biophysical and social processes (Kirchhoff et al 2013; Weaver et al 2014). This requires contributions from a wide range of

scientific disciplines and full integration of social stakeholders (Mausser et al 2013).

The discussion of different types of knowledge raises the fundamental question of what knowledge production

paradigms can contribute to delivering sustainable adaptations to growing environmental stressors in mountain regions. This is still an open question that needs full consideration by the research community.

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Supplemental material

TABLE S1 List of adaptation policy documents analyzed.

APPENDIX S1 Additional information sources to complement the content of the first column in Table 1.

APPENDIX S2 Questionnaire.

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